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MODELLING OXYGEN DEPLETION IN THE KAMINISTIQUIA RIVER THUNDER BAY, ONTARIO

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MODELLING OXYGEN DEPLETION IN THE KAMINISTIQUIA RIVER, THUNDER BAY, ONTARIO

by

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TABLE OF CONTENTS

FOREWORD

The study of the Kaministiquia River, originally planned as a waste assimilation capacity investigation in 1985, was subsequently expanded and included as a Municipal Industrial Strategy for Abatement (MISA) pilot site. Inclusion of the MISA objectives for the site study expanded the range of investigation from traditional nutrient and oxygen consuming waste concerns to include all known and suspected contaminants from point source dischargers to the river.

Part 1 of the Kaministiquia River water quality study presented the findings of water quality surveys carried out in 1986 as they relate to the assimilative capacity of the lower river. The findings focussed on the impact of oxygen consuming wastes. A traditional one-dimensional riverine model was utilized to define the dissolved oxygen depletion.

Part 2 of this series presented the findings on the thermal structure and hydrodynamics of the river based on a joint study between the Ontario Ministry of the Environment and Environment Canada.

This report, which is Part 3 in this series, presents the findings on oxygen depletion in the river based on further work of the joint study between the Ontario Ministry of the Environment and Environment Canada. The waste assimilation capacity of the lower river was evaluated utilizing two-dimensional estuary modelling techniques. The findings focus on the impact of oxygen consuming wastes, and the detailed spatial distribution of oxygen.

An investigation of the impact of toxic organic and inorganic wastes is underway utilizing the estuary models and will be presented in subsequent technical reports.

In addition to the MISA study activities, the entire Thunder Bay near shore area is under investigation as part of the Remedial Action Plan (RAP) process.

Note:

The Great Lakes Forest Products Company, which discharges to the lower Kaministiquia River, has had a change in corporate name since the writing of this report. The new name is, The Canadian Pacific Forest Products Company. All references to the former name in this report, should be changed as noted above.

ABSTRACT

A three layer DO-BOD box model was developed, calibrated and verified for the Kaministiquia River as part of the development of water quality models for the MISA program. The model accounts for BOD decay, BOD settling, reaeration, sediment oxygen demand, diffusion, heated effluent loadings and transport. Transport was calculated using the previously modified DYRESM model (McCrimmon et al. 1987) and accounts for the intrusion of cooler Lake Superior water which creates thermal stratification.

Reasonably good results with average relative errors of 20.6% and 18.6% for the calibration period of August 11-15, 1986 and the verification period of June 15-21, 1987, respectively, were achieved. Vertical diffusion rates required increases for model verification due, likely, to different physical conditions existing during the period. A better hydrodynamic model and more measurements of water levels and velocities are desired. It was found that the low dissolved oxygen levels are most sensitive to changes in BOD loadings and transport. To satisfy the provincial water quality objective of a minimum dissolved oxygen concentration of 5 (mg/L), the BOD loadings from the Great Lakes Forest Products Company would have required approximately a 75% reduction. Other management strategies were also tested with the model which could be run on an IBM PC/AT microcomputer or compatibles.

RÉSUMÉ

Un modèle de rivière à trois couches pour le calcul de l'OD et de la DBO a été mis au point, étalonné et vérifié pour la Kaministiquia dans le cadre de la création de modèles de qualité de l'eau pour la SMID. Le modèle représente la dégradation de la DBO, sa charge après sédimentation, la réaération, la demande en oxygène des sédiments, la diffusion, le volume d'effluents chauds et le transport. Le transport a été calculé à l'aide du modèle DYRESM précédemment modifié (McCrimmon et coll. 1987) et tient compte de la pénétration des eaux plus froides du lac Supérieur à l'origine de la stratification thermique.

Des résultats raisonnablement concluants (pourcentages moyens d'erreur relative de 20,6 % et de 18,6 % respectivement) ont été obtenus pour la période d'étalonnage du 11 au 15 août 1986 et la période de vérification du 15 au 21 juin 1987. Les taux de diffusion verticale ont dû être augmentés lors de la vérification du modèle, probablement à cause des conditions différentes qui prévalaient au cours de cette période. Un meilleur modèle hydrodynamique et un plus grand nombre de mesures des niveaux d'eau et des vitesses sont souhaitables. On a découvert que les endroits où le volume d'oxygène dissous était faible étaient les plus sensibles quand la charge en DBO et son transport subissaient des modifications. Pour atteindre l'objectif provincial de qualité de l'eau, soit une concentration minimale d'oxygène dissous de 5 mg/L, la DBO provenant de la Great Lakes Forest Products Company devrait être réduite d'environ 75 %. D'autres stratégies de gestion ont également été étudiées sur le modèle de simulation qui pourrait être exécuté sur un micro-ordinateur PC/AT IBM ou une machine compatible.

DISSOLVED OXYGEN MODEL FOR THE KAMINISTIQUIA RIVER, THUNDER BAY, ONTARIO

1. INTRODUCTION

The lower Kaministiquia River located near Thunder Bay, Ontario is subject to industrial pollutant loadings which often cause the river water quality, especially dissolved oxygen concentrations, to fall below desired levels (MOE 1972, 1988). The Great Lakes Forest Products Company operates the largest pulp and paper mill in Ontario which discharges to the Kaministiquia River approximately 10 km. upstream of Lake Superior (see Figure 1). Application of a riverine water quality model would normally be sufficient to determine viable solutions. However, the delta of the Kaministiquia River is unusual since cooler and cleaner Lake Superior water intrudes upstream along the river bottom, which creates a vertical thermal structure with a distinct thermocline similar to that observed in lakes. This phenomenon also results in both a horizontal and a vertical gradient of dissolved oxygen concentration since the polluted water is warmer and flows downstream nearer the surface. Therefore, a river water quality model that accounts for vertically varying concentrations is required.

In a previous study (McCrimmon et. al. 1987) flow characterisitics and water temperatures were determined for August 11-15, 1986 using a modified version of the one-dimensional dynamic reservoir simulation model, DYRESM. The river was divided into 16 connected segments which were simulated in turn using DYRESM in six-hour time steps. In this study a 3 layer 16 segment DO-BOD box model, which uses the previously determined flows and water temperatures, was developed and calibrated for the 1986 data. In addition, data for June 15-21, 1987 was obtained and used to verify the DYRESM and DO-BOD models.

2. GOALS AND OBJECTIVES

The overall goal of the Kaministiquia River Water Quality Modelling Study is to develop and verify water quality models with predictive capability for the assessment of possible management strategies for the Municipal Industrial Strategy for Abatement (MISA) program on pollution control for rivers of the same type. The goals and objectives of the MISA program were laid out in a White Paper from MOE (MOE 1986). The objective of this study is to develop a Dissolved Oxygen - Biochemical Oxygen Demand (DO-BOD) model incorporating not only the multi-source, heated effluent conditions but also the modulations on the DO-BOD concentrations by the intrusion of the relatively cooler and denser lake water.

The present report describes (i) the DO-BOD model, (ii) the DO-BOD model calibration results, and (iii) the verification results of the DYRESM and DO-BOD models using the 1987 data. Also presented is a sensitivity analysis of DO and BOD to changes in model parameters, boundary conditions and loadings.

3. DO-BOD MODEL

The method for predicting DO and BOD concentrations involves a number of sequential steps, the results of which are used in ensuing steps. A flowchart outlining these steps is presented in Figure 2(a). Basically, the steps involved are 1) predict water temperatures and flow characteristics using DYRESM, 2) calculate the equivalent box temperatures and transport for use in the DO-BOD 3 layer box model, 3) calculate the required diffusion rates for temperature using the box model, 4) check transport and diffusion using the box model to predict sodium, and 5) predict DO and BOD.

The DO-BOD model developed predicts the DO and BOD concentrations of 3 layers for each of the 16 river segments for a total of 48 boxes. The selection of a 3 layer box model was based upon the temperature profiles which indicated the existence of a 1.5 m thick epilimnion and a hypolimnion below a depth of 4.5 m, on average. Also, in the upper and lower layers, the horizontal flows were all downstream and upstream, respectively. The middle layer then covers the thermocline region which includes the vertically varying horizontal velocity zero point. Thus, the DO-BOD model is a two-dimensional model.

As displayed in the schematic diagram of a typical surface box in Figure 2(b), the DO-BOD box model accounts for horizontal and vertical flow, BOD decay, reaeration, sediment oxygen demand, vertical diffusion, external loadings and BOD settling. Downstream of the first river reach the middle layer boxes often contained 10 to 20% upstream flow. Since only a net downstream flow is used in the model for the middle layer then a horizontal diffusion in the middle layer is included in an attempt to account for the neglected effects of upstream flow in the DO-BOD model.

The equations used in the DO-BOD model are

$$V\frac{dDO}{dt} = -u\,V\frac{dDO}{dx} + K_d V\frac{d^2DO}{dz^2} - K_1 V\,BOD\frac{DO}{DO + C_H} + K_2 V(DO_S - DO)$$

$$- SOD\,A_{sed} + DO_L \qquad (1)$$

$$V\frac{dBOD}{dt} = -u\,V\frac{dBOD}{dx} + K_d V\frac{d^2BOD}{dz^2} - K_1 V\,BOD\frac{DO}{DO + C_H} - W\,A\,BOD + BOD_L \qquad (2)$$

and for the middle layer add the following

$$+ K_{EX}\,V\frac{d^2C}{dx^2}$$ where C = DO for equation (1)

C = BOD for equation (2)

where

V = box volume (m^3)
BOD = biochemical oxygen demand (g/m^3)
DO = dissolved oxygen concentration (g/m^3)

t = time (d^{-1})
u = horizontal velocity (m/d)
x = horizontal distance (m)
z = depth (m)
K_d = vertical diffusion constant (m^2/d)

K_1 = BOD decay rate (d^{-1})

C_H = half saturation constant (g/m^3)

$DO_S = 14.48 - 0.36T + 0.0043T^2$ = saturated [DO] (g/m^3)

T = water temperature of the top box (celcius)

K_2 = reaeration constant (d^{-1})

SOD = sediment oxygen demand ($g/m^2/d$)
A_{sed} = sediment surface area of box (m^2)

W = BOD settling rate (m/d)
A = horizontal area of box bottom (m^2)
DO_L = DO external loading (g/d)

BOD_L = BOD external loading (g/d)

K_{EX} = horizontal diffusion rate (m^2/d)

Through experimentation of different model equation solutions, a predictor-corrector method using a 1/2 hour time step was selected for the DO-BOD model. It should be noted that to conserve mass the flow rates from the DYRESM results had to be used explicitly. In more detail, the model equations were solved as follows:

for time step 1: explicit solution

$$\frac{C^{n+1} - C^{n}}{t} = f(C^{n})$$

where C = concentration
n = time step level (n t=t)
t = time

for remaining time steps: 1) predictor

$$\frac{\tilde{C}^{n+1} - C^{n-1}}{2\ t} = f(C^{n})$$

2) corrector

$$\frac{C^{n+1} - C^{n}}{t} = f\left(\frac{\tilde{C}^{n+1} + C^{n}}{2}\right)$$

For each time step, the predictor calculation is performed on all boxes then the corrector is performed for all boxes to achieve the simulated values.

4. DATA BASE

Flow rates and water temperatures for August 11-15, 1986 were taken from the previous study (McCrimmon et. al. 1987). Other data required for calibration of the DO-BOD model, such as loadings and observations, were supplied by the Ontario Ministry of the Environment (MOE). The 1987 data used for verifying both the DYRESM and DO-BOD models was also supplied by MOE. In this section, the available data, calculated and estimated data and assumptions related to the data and model are presented for calibration and verification of the DO-BOD model and verification of the DYRESM model.

The Kaministiquia River is located in northern Ontario near Thunder Bay. The stretch of the river under investigation extends from the river outlet at Lake Superior to approximately 10 kilometres upstream, and includes the McKellar and Mission River branches, as depicted in Figure 1. The points A through P in Figure 1 indicate the cross-section locations at which parameter measurements were made by the MOE. By using these points and the added point Z, which is the location of the river's main pollutant source, as boundaries, 16 river sections were created for modelling purposes.

4.1 DO-BOD Model Calibration Data

The DO-BOD model was calibrated over the DYRESM calibration period of August 11-15, 1986. The flows, water temperature and hypsometric data were taken from the DYRESM calibration data base and results. The DO and BOD observations were supplied by MOE and included for most cross-sections 1) DO profiles at the right, middle and left on August 15, 2) 4-hourly surface values of DO and BOD for August 11-14 and 3) hourly surface values of DO for August 11-14. At each cross-section the right, middle and left DO profiles were averaged. The river segment values were then estimated as the average of the upstream and downstream cross-section profiles. These profiles were used also as the initial conditions. Since there are no BOD observations below the surface, the initial values of the middle and bottom layers were assumed to be cleaner due to the upstream flow of water from Lake Superior and were set equal to the upstream concentration of 0.4 g/m^3.

4.2 Verification Data

The DYRESM and DO-BOD models were verified over the period June 15-21, 1987. The water levels, velocity profiles and hypsometric data were taken from the 1986 data base. The DYRESM calibration data base was used for verification but with the following changes:

1) The 1987 values of daily Kakabeka Falls flow rates (for scaling velocity profiles), daily wind speed, daily air temperature, daily precipitation were inserted.

2) Daily wind directions were utilized instead of 6-hourly.

3) Estimated constant daily short wave radiation and vapour pressure were used.

4) The 1987 daily temperature profile observations were utilized, which were available at most cross-sections on each day, for initial conditions and simulation comparison.

The flow rates and water temperature required for the DO-BOD model were taken from the DYRESM model. The average vertical diffusion rates required to obtain the desired box temperatures were calculated using the 3 layer box model. The DO observations consisted of daily profiles at most cross-sections. These were averaged to obtain river segment values for the initial conditions and for simulation comparison. The 1986 initial BOD values were used since there were no BOD observations for 1987.

5. RESULTS

The development of a calibrated and verified DO-BOD model for the lower Kaministiquia River involved, firstly, the simulation of flows and water temperatures using a modified version of DYRESM, secondly, the calculation of vertical diffusions for temperature using the 3 layer box model, thirdly, the simulation of sodium to check the transport processes of the 3 layer box model, and lastly, the application of the 3 layer box model for DO-BOD. In this section, the results of the above steps will be presented except for the calibration of DYRESM, which was presented previously (McCrimmon et. al. 1987).

5.1 Sodium Simulation Using the 3 Layer Box Model

The simulation of temperature using the 3 layer box model is a good test of the model and permits the calculation of diffusion rates. However, temperature is influenced by factors such as surface heat fluxes. Therefore, to truly test the transport of the model, especially with respect to loadings at the ZB diffuser, the simulation of sodium (Na) was attempted. Na is relatively conservative and nonreactive and, like BOD, would be low in concentration if there was no loading from the diffuser.

Surface Na observations were available for 1986 for all cross-sections except for Z, E and N. Also, the effluent loadings from diffusers at ZB and BC were known (740 and 290 g/s respectively). Using the calculated temperature diffusion values in the model resulted in a mean relative error of 11.6%. In addition, all of the simulated values fell within the range of observations of each segment.

Since the diffusion rates of temperature and Na are likely different the values were varied to try to reduce the error. It was found that reducing the diffusion rates 50% for the diffuser segments and increasing the rates for the remaining segments 5 times decreased the mean relative error to 6.0%, while also maintaining the simulated values within the range of observations. These simulated values and the means and ranges of observations are plotted in Figure 3. The good results indicate the transport components of the 3 layer box model are reasonable. However, this testing of the model does not directly consider the two lower layers for which there are no sodium observations.

5.2 DO-BOD Model Calibration

The calibration of the DO-BOD model involved varying model parameters to minimize the difference between simulated and observed DO and BOD concentrations. Only diffusion rates and the biochemical, as opposed to physical, parameters were considered.

The following values of the calibration parameters were found to result in the smallest differences between simulated and observed values.

BOD decay rate = 0.9 (d^{-1})

Reaeration rate = 0.05 (d^{-1})

SOD rate = 0.15 ($g/m^2/d$)

half saturation constant = 1.5 (g/m^3)

horizontal diffusion rate = $2.1*10^6$ (m^2/d)

diffusion at ZB, upper and lower interface = $3.2*10^{-2}$ (m^2/s)

diffusion at BC, upper interface = $2.7*10^{-4}$ (m^2/s)

lower interface = $6.8*10^{-5}$ (m^2/s)

diffusion at rest, upper and lower interface = 0. (m^2/s)

The resulting average relative error was 20.6% and is broken down for each layer and parameter in Table 1. The calibrated vertical diffusivities for the pollutants at ZB and BC are found to be 2.25 times the vertical thermal conductivities obtained using the computed temperature. The vertical diffusivities at the other segments were very small (< 10^{-6}) and, therefore, a value of zero was used. The simulated and observed values for the top and bottom layers for the last three days of the simulation period are shown in Figures 4 and 5. It can be seen in these Figures that the model predicts the horizontal variability of DO and BOD quite well.

Included in Figures 4 and 5 for each segment are vertical bars above and below the simulated values representing DO source and sink components, respectively, summed over the previous 6 hours. The

TABLE 1. MEAN RELATIVE ERRORS

	1986 CALIBRATION DATA	1987 VERIFICATION DATA
[DO] TOP LAYER	18.5%	18.6%
MIDDLE LAYER	36.2%	24.9%
BOTTOM LAYER	6.2%	11.7%
[BOD] TOP LAYER	23.7%	-
AVERAGE	20.6%	18.6%
TEMPERATURE	5.8%	5.9%

unshaded areas represent the source of DO from reaeration for the top layer but is indistinguishable in Figure 4 because of the small reaeration coefficient. The unshaded area represents the source from external loadings in the bottom layer in Figure 5. The darkest shaded areas represent the change in DO due to transport. In Figure 4, the transport is shown to be a large source of DO in the top layer of the upper segments. This is a result of the relatively higher upstream [DO]. The area shaded with right to left rising lines represents the change in DO due to diffusion. The diffusion components in Figures 4 and 5 are largest at the diffuser segments and indicate DO is diffusing out of the more oxygen-rich top layer into the more polluted bottom layers. The diffusion rates for the non-diffuser segments were set to zero so no diffusion is evident for these segments in 1986. The fourth component displayed represents BOD decay and SOD and, therefore, is always a sink of DO and is at the bottom of the vertical bars in Figures 4 and 5. This component is the dominant sink of DO and is due mainly to decay since the SOD rate is relatively small.

The time series of DO and BOD at the surface of each segment are plotted in Figures 6 and 7, respectively, with observations at the upstream and downstream cross-sections included. In general, the DO and BOD fit the observations but short time scale variations are not reproduced by the model due mainly to the daily time step resolution of DYRESM. This is evident for segment LM in Figure 6, for example. Due to relatively high upstream concentrations of DO, low upstream concentrations of BOD and higher flow rates during the first half of the calibration period, the DO levels are higher and the BOD levels are lower as especially evident at ZB. This shows the importance of the flow characteristics on the DO-BOD levels. The substantial difference between the observed and simulated BOD at ZB on August 11 could be due to insufficient vertical transport or diffusion of BOD from the diffuser. However, it is more likely due to overestimating the flow rate on August 11, which was estimated to be twice as large as the subsequent days based upon the flows at Kakabeka Falls.

A three-dimensional representation of the study area with concentrations indicated by different shadings is represented for DO and BOD for August 15, 1986 in Figure 8. This figure shows that the polluted water discharged at the bottom of segment ZB generally flows in an upward and downstream direction and, due to the time dependent decay of BOD, the minimum [DO] occurs in the surface layer between segments EF, HI and JK. Downstream of JK the BOD levels are lower due to decay so that flow from the lower layers, diffusion and reaeration cause a slight increase in DO levels. Also evident is upstream flow of polluted water into the bottom layer of AZ from ZB. The cross-sectional area of the bottom layer at A is small, due to the rivers shallowness at this point, so there is little flushing flow from upstream, which keeps the [DO] low and the [BOD] high. However, it should be noted that a lack of velocity measurements in this area precludes the assumption that there is upstream flow of polluted water into AZ.

5.3 DYRESM Verification

The data base used for verifying DYRESM from June 15-21, 1987 was outlined in Section 4. The major differences from the calibration data base are the differing flows and meteorological conditions. Also, there are more observations, especially in the lower layers, than in 1986. The remaining model parameters were the same as the 1986 data.

The first simulations of the Kaministiquia River using the verification data are plotted in Figure 9 for every other day. The simulated values compared reasonably well (root mean square error (rms) = 1.15^{o}C and average relative error = 5.9%) with the observed profiles. These results are almost as good as the 1986 data calibrations (rms = 0.93^{o}C and average relative error = 5.8%) which is encouraging since the 1987 observations are much more numerous and encompassing. The future acquisition of the daily solar radiation and vapour pressure could improve the simulations on a daily basis. The DYRESM model was assumed verified and no further parameter modifications were performed.

5.4 DO-BOD Model Verification

Verification of the DO-BOD 3 layer box model was attempted for the period June 15-21, 1987. The model inputs of flow and water temperature were taken from the DYRESM verification results and vertical diffusion values were recalculated using the 3 layer box model for temperature because the physical conditions changed. These inputs were then used in conjunction with the calibrated model parameter values, which were kept fixed, to verify the model.

The simulated DO values using the verification data were reasonably good with an average relative error of 18.6%. As seen in Table 1, this error is actually better than the calibrated error of 20.6% but the verified error is slightly biased to DO since no BOD observations were available. While the DO error for the bottom layer increased 5.5% for the verification simulations, the middle layer decreased 11.3%. The recalculated diffusion values used in the verification model are

diffusion at ZB, upper interface = 1.8×10^{-4} (m^2/s)

lower interface = 2.1×10^{-3} (m^2/s)

diffusion at BC, upper interface = 1.1×10^{-4} (m^2/s)

lower interface = 2.3×10^{-5} (m^2/s)

diffusion at rest, upper interface = 1.0×10^{-4} (m^2/s)

lower interface = 2.5×10^{-5} (m^2/s)

which correspond to 2.25 times the temperature rates at ZB and BC and 2.5 times the average temperature rates of the remaining segments. The simulated and observed DO and BOD values are plotted in Figures 4 and

5 for the last three days of the verification period. As compared to the 1986 observations, the [DO] in the bottom layer is evidently lower in 1987. This indicates that possibly the flow regime differs slightly from the 1986 period in that the upstream flow lake water intrusion along the river bottom does not extend as far upstream as in 1986. Also, the flow rates from August 12 to 15, 1986 ranged from 17.6 to 19.7 m^3/s whereas they ranged from 21.2 to 23.2 from June 17 to 21, 1987, which suggests the varying flow regimes. The higher downstream flows of 1987 would likely push back the upstream intrusion of Lake Superior water, which could cause the observed decrease in DO at the bottom. For example, on the last day of the 1986 and 1987 periods the observed [DO] of the bottom layer at cross-section C was 6.9 (mg/l) in 1986 but was only 3.4 in 1987. This suggests less lake water, which was cleaner, reached cross-section C in 1987. It is possible that the water levels of the river and Lake Superior in 1987 are different from 1986 resulting in different velocity profiles.

The time series of the top layer DO and BOD concentrations for each segment are presented in Figures 6 and 7. As was the case for the 1986 plots, the verification simulated DO values generally fit the observations and indicate the lowest DO levels occur in the middle segments. When the flow rates increase on June 18, there is an increase in the [DO], as is evident especially for segments BC to EF in Figure 6. This correlation of higher DO concentrations with higher flow rates was also evident in the calibration simulations. Similarly, the BOD levels decrease June 18 because the upstream BOD values are lower and the BOD decay rates increase due to higher DO levels.

Three-dimensional representations of the rivers DO and BOD concentrations are presented in Figure 10. The pollutant loadings at Z8 flow mostly vertically upwards and downstream as was seen for 1986 in Figure 8. The main difference from 1986 is that the [DO] of the lower layers is smaller in 1987 due mainly to increased diffusion rates, which cause DO to diffuse upwards to the less oxygen-rich layers.

5.5 DO-BOD Model Sensitivity Analysis

The sensitivity of DO and BOD concentrations to variations of model parameters and loadings was investigated using the 1986 data base. To standardize the sensitivity score, parameters and loadings were varied plus and minus 20%, one at a time, and the change in mean values of DO and BOD of each layer were recorded. The results of the analysis are presented in Table 2.

Table 2 is divided into 3 parts representing, first, the biochemical parameters, second, the loading and boundary conditions, and third, the diffusion rates. Of the biochemical parameters, DO and BOD are most sensitive to the BOD decay rate. The reaeration and SOD rates used in the model are at the lower end of normal values and do not noticably effect DO and BOD when varied 20%. Reaeration and SOD rates that are 500% larger would not be unreasonable but, as seen in Table 2, such values result in a maximum relative change of only 3% (absolute change of +15% for the top layer [DO] when reaeration is increased 500%).

The large changes in DO and BOD displayed in the second part of Table 2 indicate the boundary conditions and BOD loading strongly

TABLE 2. DO-BOD MODEL SENSITIVITY ANALYSIS SUMMARY-
PERCENT CHANGE IN LAYER AVERAGE CONCENTRATION

	DECAY		REAERATION			C_H		SOD		
	+20%	-20%	+20%	-20%	+500%	+20%	-20%	+20%	-20%	+500%
TOP [DO]	-10	+13	+1	-1	+15	+4	-4	0	0	-2
MIDDLE [DO]	-5	+6	0	0	+1	+1	-2	0	0	-2
BOTTOM [DO]	-1	+2	0	0	0	0	0	0	0	-4
TOP [BOD]	-4	+6	0	0	-2	+2	-2	0	0	+1
MIDDLE [BOD]	-5	+7	0	0	0	+2	-2	0	0	+1
BOTTOM [BOD]	-4	+5	0	0	0	+1	-1	0	0	0

	BOD LOAD		DO LOAD		U/S [DO]		D/S [DO]	
	+20%	-20%	+20%	-20%	+20%	-20%	+20%	-20%
TOP [DO]	+17	-12	+1	-1	+19	-17	+23	-4
MIDDLE [DO]	+8	-7	0	0	+8	-8	+19	-11
BOTTOM [DO]	+1	-1	0	0	+1	-1	+15	-13
TOP [BOD]	-20	+22	0	0	-3	+4	-4	+1
MIDDLE [BOD]	-19	+21	0	0	-2	+3	-3	+1
BOTTOM [BOD]	-18	+18	0	0	-1	+1	-1	0

	K_{EX}		DIFF(ZB,BC)		DIFF(REST)	
	+20%	-20%	TEMP.	Na(=TEMP/2)	TEMP.	Na(=5*TEMP)
TOP [DO]	+2	-1	+2	+6	+10	+23
MIDDLE [DO]	+3	-3	-2	-5	-7	-13
BOTTOM [DO]	0	0	0	-1	-9	-27
TOP [BOD]	0	0	-5	-14	-6	-14
MIDDLE [BOD]	0	0	+4	+10	+3	+6
BOTTOM [BOD]	0	0	+22	+49	+4	+20

influence conditions in the river. The sensitivity of the boundary [BOD] was not investigated since the values were very small compared to the diffuser loadings. The combination of the sensitivity of DO and BOD to changes in the BOD decay rate and the BOD loadings, especially in the surface layer where the minimum [DO] occurs, clearly shows their importance. Also, the sensitivity to changes in the boundary concentrations and the insensitivity to changes in reaeration and SOD indicates the flow patterns are important.

In the third part of Table 2 the sensitivity results for diffusion rates are presented. The horizontal diffusion appears to have a small effect on layer concentrations. However, K_{EX} effects only the segments below the first branch so that the percent change in the layer average concentrations underestimates the effects of the horizontal diffusion on the lower segments. The vertical diffusion rates calculated for temperature and calibrated for sodium were used in the sensitivity analysis instead of plus or minus 20% (recall the calibrated DO-BOD model used (a) 2.25 times the temperature values for segments ZB and BC and (b) zero for the remaining segments). The [BOD] is sensitive to the diffuser diffusion rates because of the large concentration gradient in ZB and BC caused by the effluent loadings. The diffusion rates in the remaining segments affect both DO and BOD significantly because of the existing gradients resulting from the BOD decay and flow patterns.

A pie chart representing the relative effects of the three parts of Table 2 for the top layer is presented in Figure 11(a). The figure indicates all three components are important parts of the model. The pie chart in Figure 11(b) presents the relative importance of the kinetic coefficients (part 1 of Table 2). The values in Figure 11(b) represent the absolute change in surface DO resulting from the change of each parameter from -20% to +20%. In Figure 11(b), the large areas of decay and half-saturation as compared to the remaining non-effluent dependent components of the model clearly displays the importance of the decay of the effluent loading.

The effects of changing the BOD loading were investigated in more detail since the DO levels were found to be very sensitive to varying effluent loadings. By reducing the BOD loading at the ZB diffuser in multiples of 10% of the original loading, the [DO] of the top and bottom layers of segments GJ on the last day of the calibration and verification periods were plotted in Figure 12. The top layer concentrations increased with decreased BOD loading, for both 1986 and 1987, as expected. The bottom layer concentration of GJ for 1986 was virtually unaffected by reduced BOD loading since the only transport into this box is from downstream. Conversely, the 1987 bottom concentration does change with changing loading. This effect is due to vertical diffusion, which was previously set to zero for the 1986 calibration simulations. Also indicated in Figure 12 is the amount of BOD reduction required to meet the provincial water quality objective (PWQO) of a minimum [DO] of 5 (mg/l). The load reduction required without changing other parameters would have been, approximately, 69% for 1986 and 74% for 1987. For example, when the BOD loading at ZB is reduced 80% then the resulting simulated DO concentrations, as depicted in Figure 13, are all above 5 (mg/l). Other management strategies, however, would have also been used, such as the use of oxygen diffusers and the adjustment of river flows and water levels. As an example of this strategy, an oxygen diffuser was hypothetically used to insert 10,000 kg/d of DO throughout segment BC in the model. The DO concentrations at the end of the 1987 verification period, as simulated by the model, would then be as presented in Figure 14. At segment BC and downstream middle and upper layer boxes the DO concentrations are noticably higher than the verification values, as previously presented in Figure 10. Though these DO levels are still below the PWQO for most segments, it is evident that there are other possible management strategies besides reducing loadings.

A plot similar to Figure 12 was made for segment AZ, which is the segment with the lowest simulated bottom layer [DO] and is presented in Figure 15. The top layer concentrations are relatively insensitive to BOD loading changes since they are dominated by flow from upstream. The bottom box of AZ is simulated as receiving most inflow from the ZB bottom box which receives Great Lakes Forest Products Company effluent loadings. Therefore, the AZ bottom box is very sensitive to the BOD loadings as evident in Figure 15. Note, however, that the surface box of GJ in Figure 12 reaches lower DO levels than the AZ bottom box but the required BOD reduction to achieve the PWQO of 5 (mg/l) in AZ is approximately the same (67% for 1986 and 77% for 1987) as for GJ. Also, as previously discussed, the upstream flow from ZB to AZ may not be as assumed in the model.

Monte Carlo simulations for BOD loading were carried out at different flow rates to better understand the probability of reaching certain minimum DO levels. The results of the simulations are presented in Figure 16. The means and standard deviations of flow and BOD loading at the ZB diffuser were calculated using the data from the calibration and verification periods. Flow rates were set to five different values based on its mean and standard deviation (see Figure

16). At each of the five flow rates, the DO-BOD model was executed for 100 BOD loadings, which were generated to fit a normal distribution with the observed mean and standard deviation, for a total of 500 program runs. Each run used averaged 1986 and 1987 conditions (e.g. initial concentrations and diffusion rates) and lasted five days. The relative number of occurences of certain DO concentrations at the surface box of segment GJ on the fifth day is indicated in Figure 16 by the horizontal bars. The results show that at lower flow rates the [DO] is lower and is also less affected by changing the BOD loading. Conversely, at higher flow rates the [DO] is (i) higher due to the higher supply rate of DO from upstream and (ii) is more sensitive to the BOD loading as indicated by the larger simulated range of DO. The importance of these results is that it appears that to remedy low DO levels the flow rates must be considered in addition to reduction of the BOD loadings.

6. CONCLUSIONS

A DO-BOD 3 layer box model utilizing a predictor-corrector solution method and a 1/2 hour time step was developed, calibrated for the period August 11-15, 1986 and verified for the period June 15-21, 1987. The modified DYRESM model, which was calibrated previously (McCrimmon et. al. 1987) and is used to calculate flows and water temperatures for the 3 layer box model, was also verified in this study.

Calibration of the DO-BOD model, which involved changes of the bio-chemical parameters and diffusion rates, resulted in an average relative error of 20.6%. The lowest DO levels were simulated to occur in the surface layer between segments EF, HI and JK. In general, the spatial variability and areas of low DO were simulated well.

Verification of the DO-BOD model over the period June 15-21, 1987 required the application of the modified DYRESM to obtain the flows and water temperatures. This verification of DYRESM resulted in a root mean square error of 1.15^{o}C and an average relative error of 5.9%, which are very similar to the errors obtained in the calibration simulations and appear acceptable.

The flows and water temperatures from the DYRESM verification simulations were used for the DO-BOD model verification. The initial simulations using the calibrated parameter values resulted in reasonable values except for the bottom [DO], which ranged up to 3 g/m^3 too high. Increasing the diffusion rates from the calibrated value of zero to 2.5 times the temperature calculated rates of all segments excluding the diffuser segments decreased the mean relative error to 18.6%, which is lower than the calibration error of 20.6%. The required increase of the diffusion rates is likely due to different velocity profiles in 1987 caused, for example, by different water levels, though no observations are available to investigate this possibility. This hypothesis is based on the DO observations of the lower layer, which indicate the upstream flow from Lake Superior did not extend as far upstream as in 1986. The DO-BOD model was considered verified but this should be approached with caution since there were no BOD observations during this period.

Reasonable simulations of DO, BOD and water temperature using the modified DYRESM model and the DO-BOD model indicate the models are useful. The recalibration of the diffusion rates in the DO-BOD model during verification suggest the need for more observations of velocities and water levels and possibly the need for a better hydrodynamic model. Also, detailed information on the loading is needed since the BOD loading is the most sensitive part of the model.

ACKNOWLEDGEMENT

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MOE, 'Kaministiquia River Water Quality Study, Part 1: Waste Assimilation Capacity', S.R. Klose, April 1988.

APPENDIX - FIGURES

LIST OF FIGURES

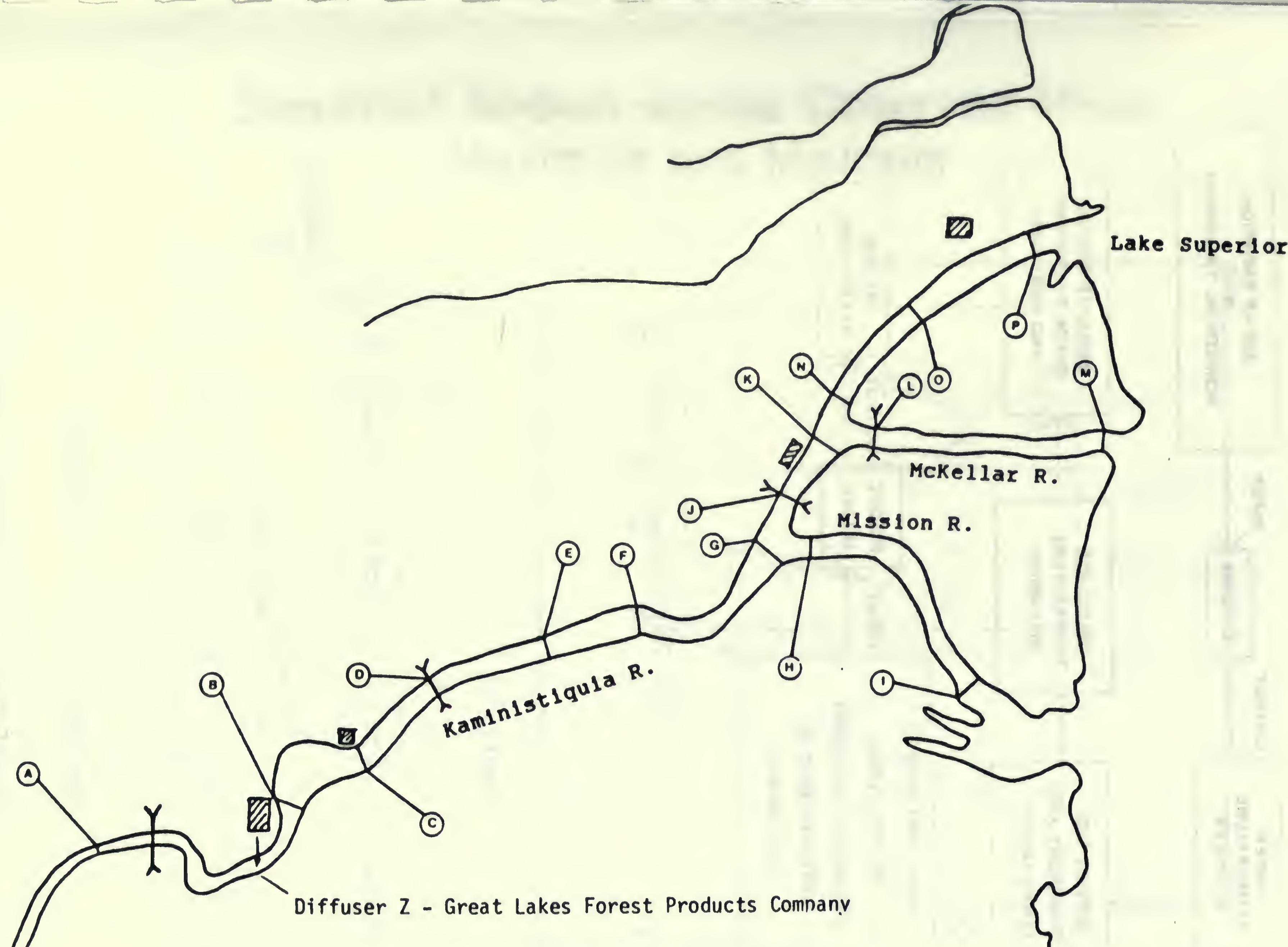


Figure 1. The Lower Kaministiquia River Study Area

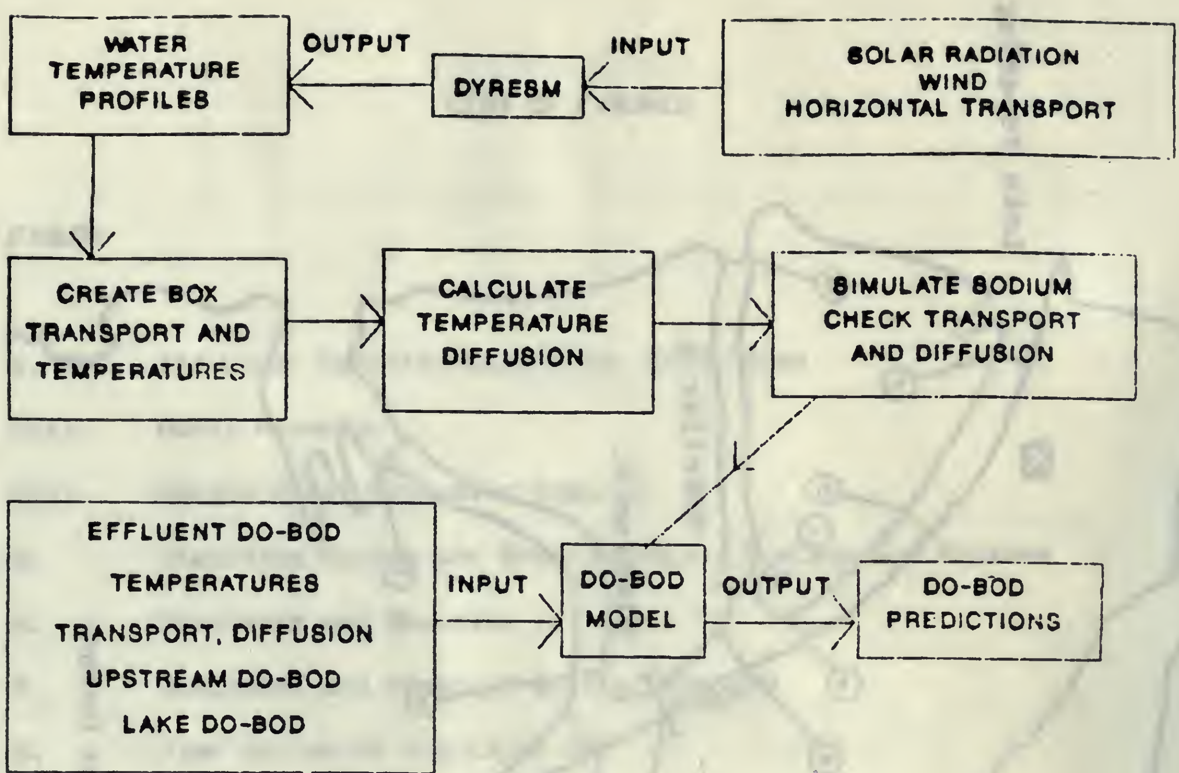


FIGURE 2(a). MODEL FLOWCHART

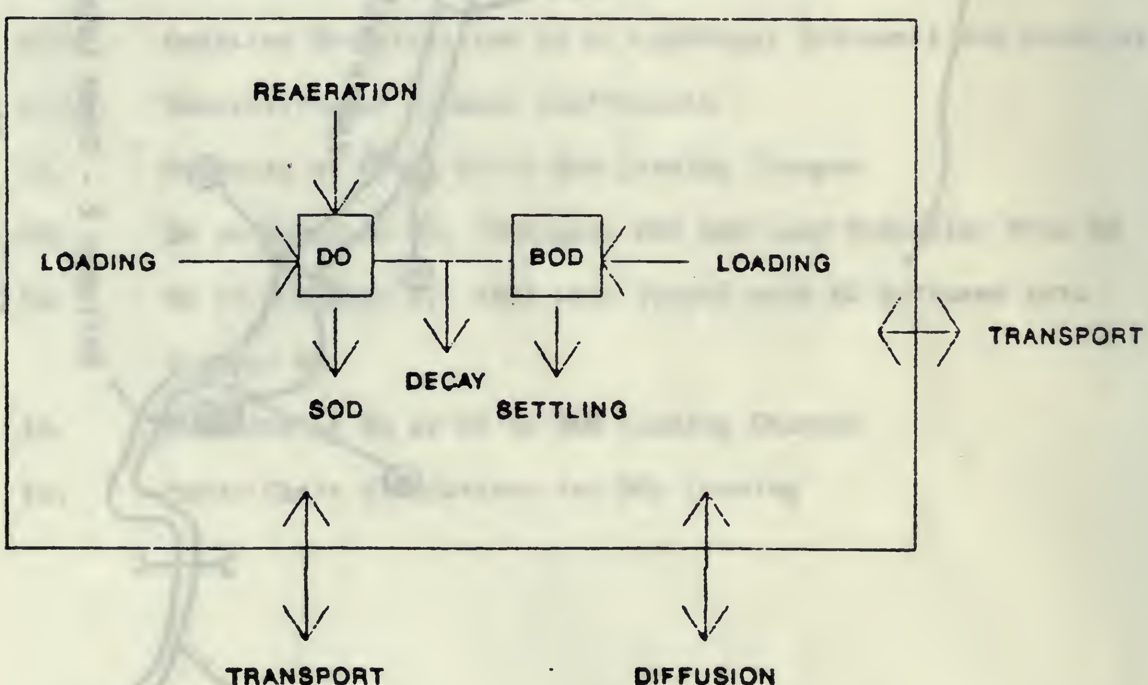


FIGURE 2(b). DO-BOD SCHEMATIC DIAGRAM

Simulated Sodium versus Observed Mean, Maximum and Minimum

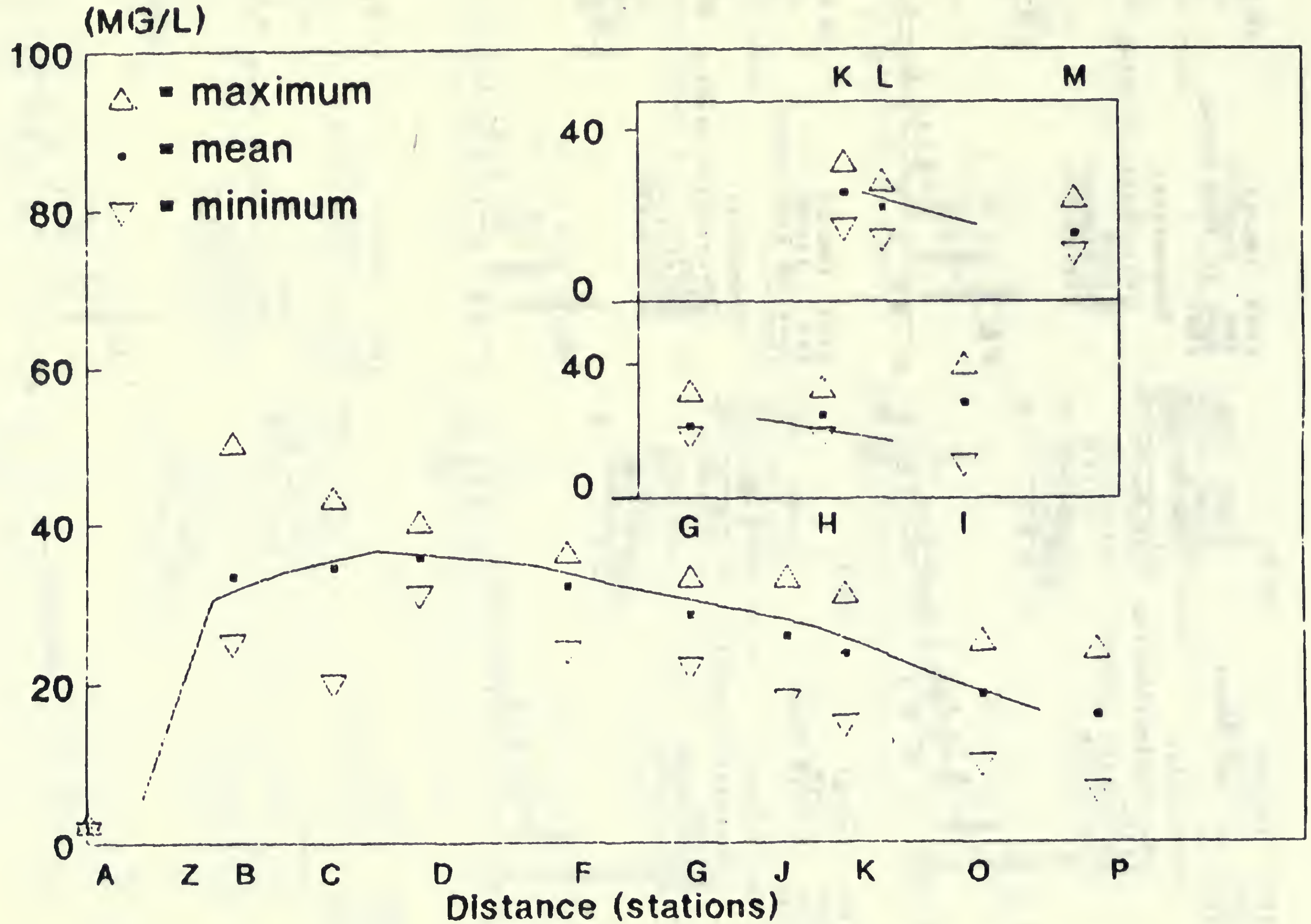


Figure 3.

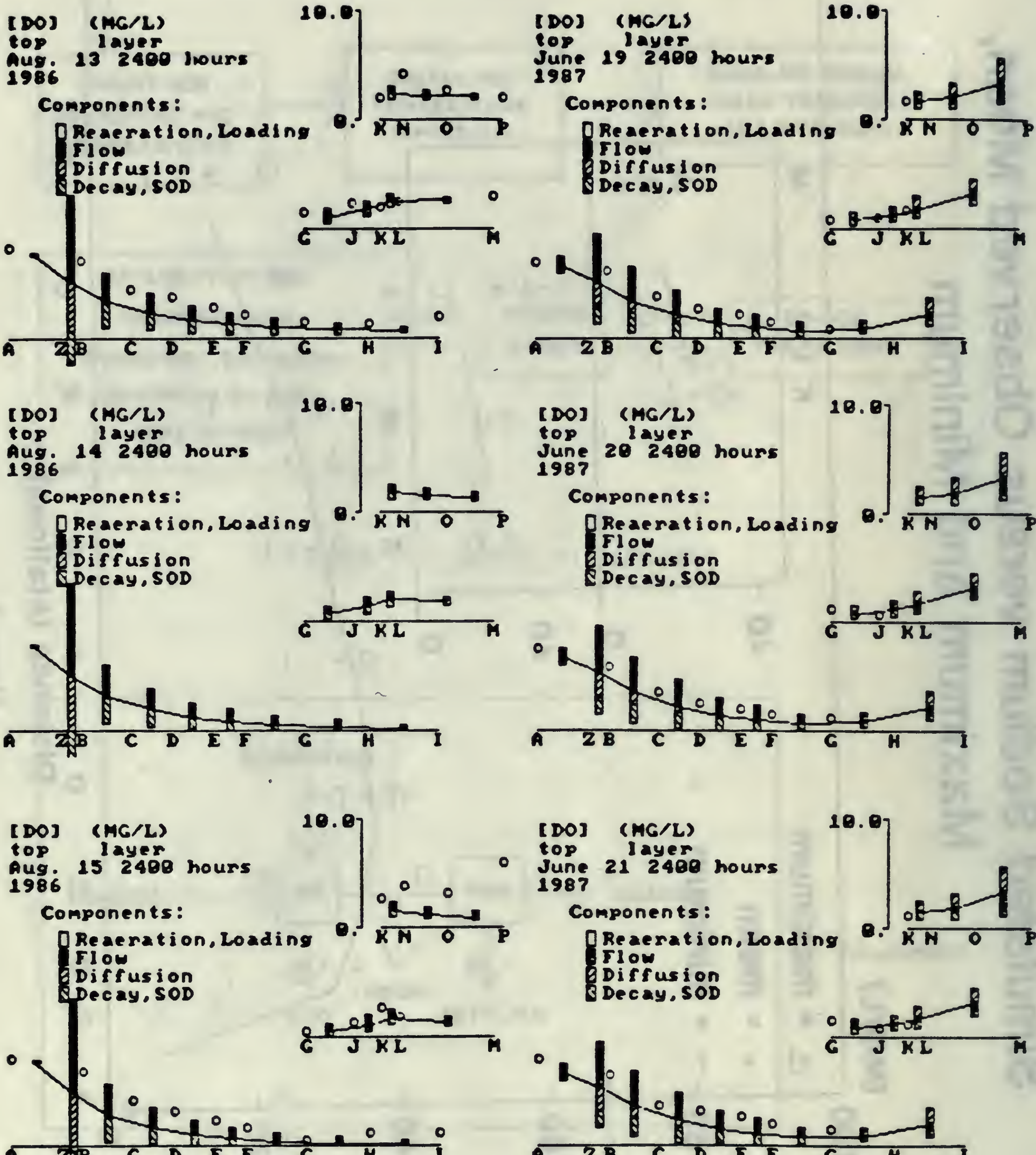


Figure 4. Simulated and Observed Top Layer DO

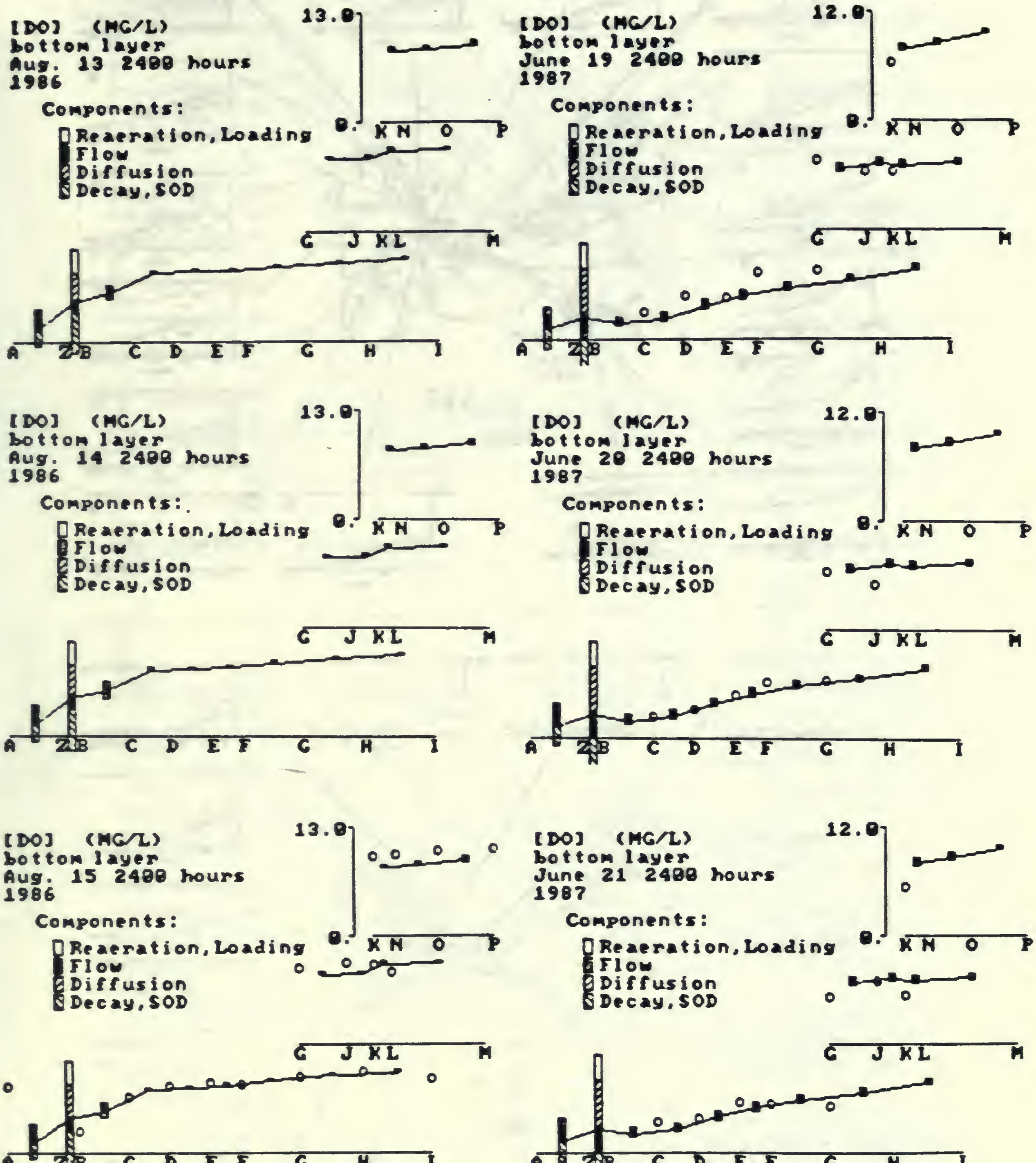
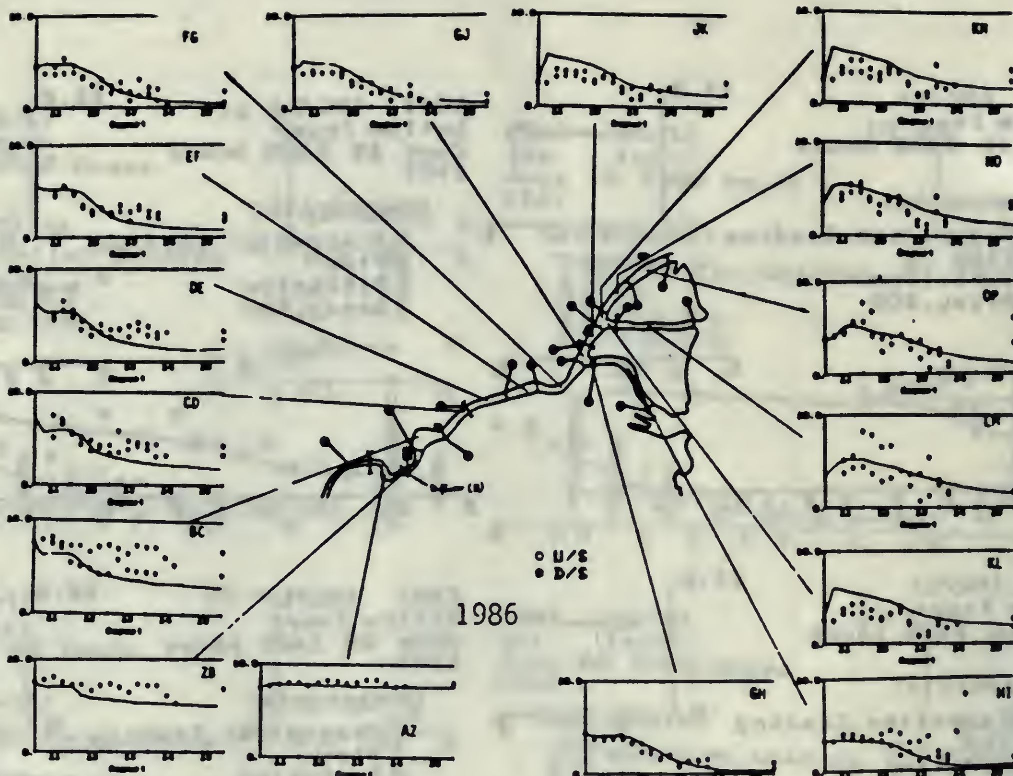


Figure 5. Simulated and Observed Bottom Layer DO



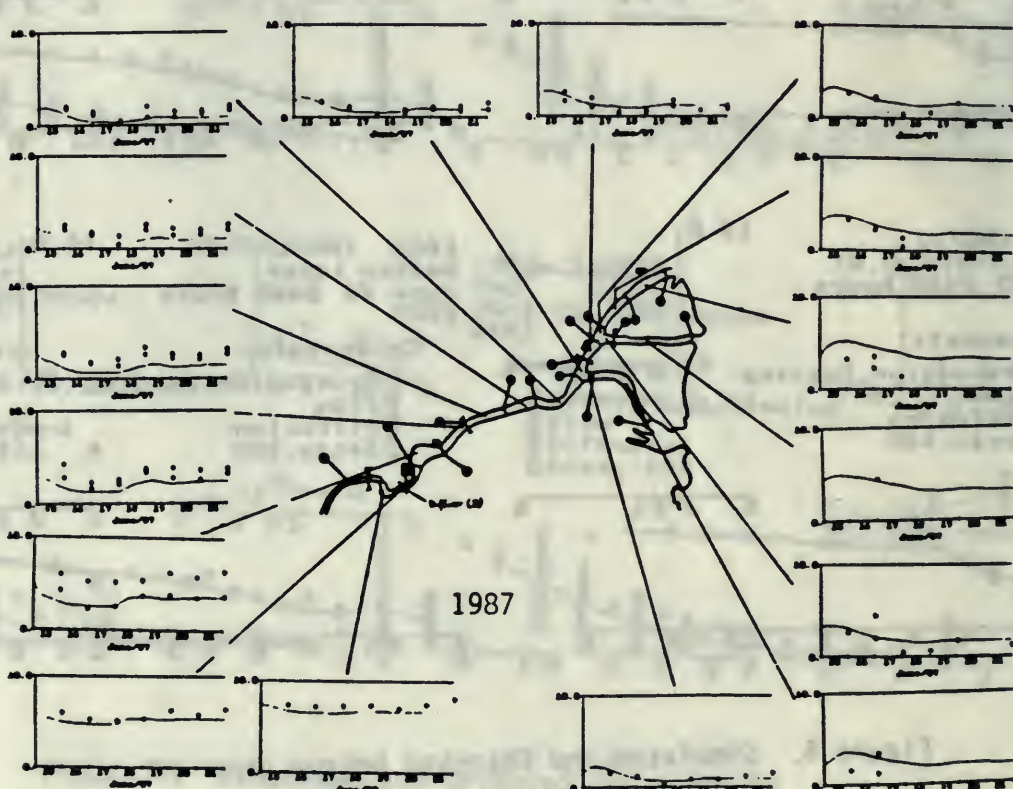


Figure 6. Time Series of Top Layer DO

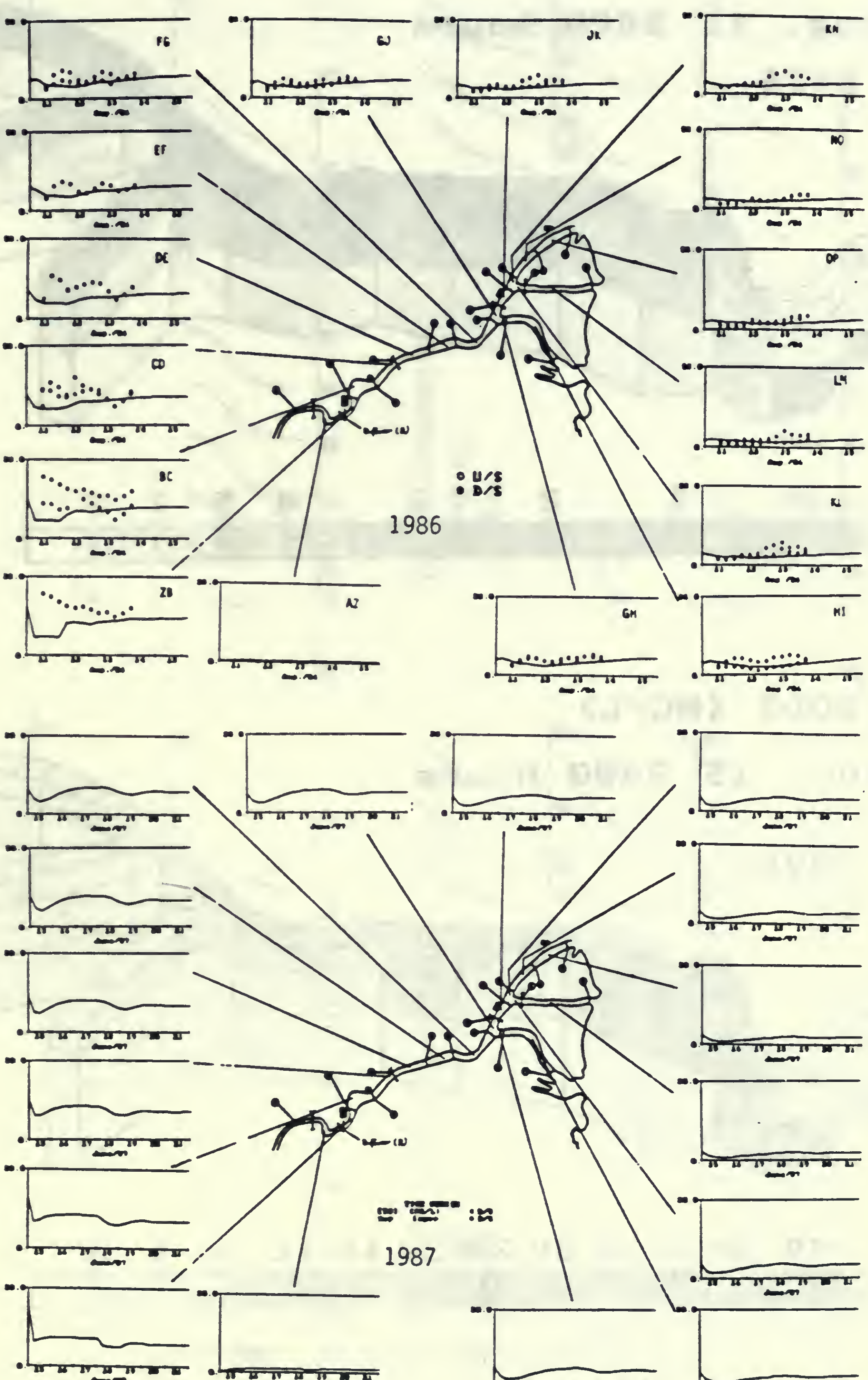
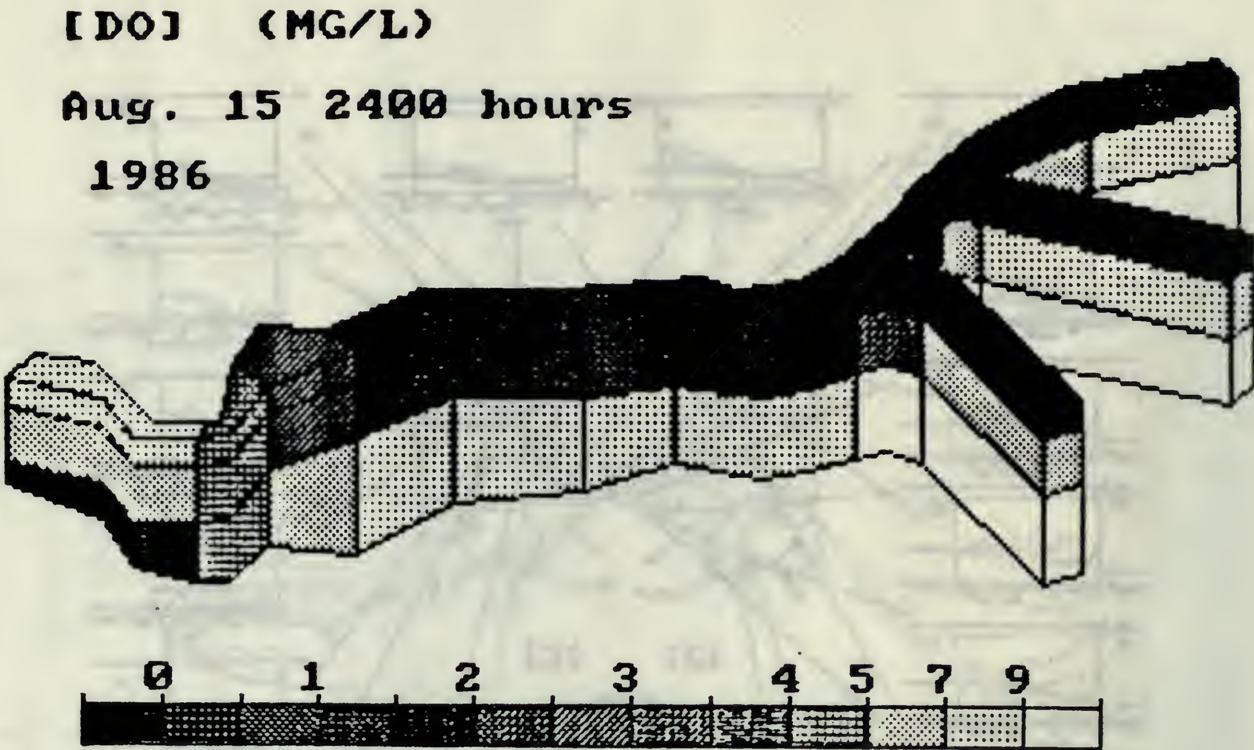


Figure 7. Time Series of Top Layer BOD



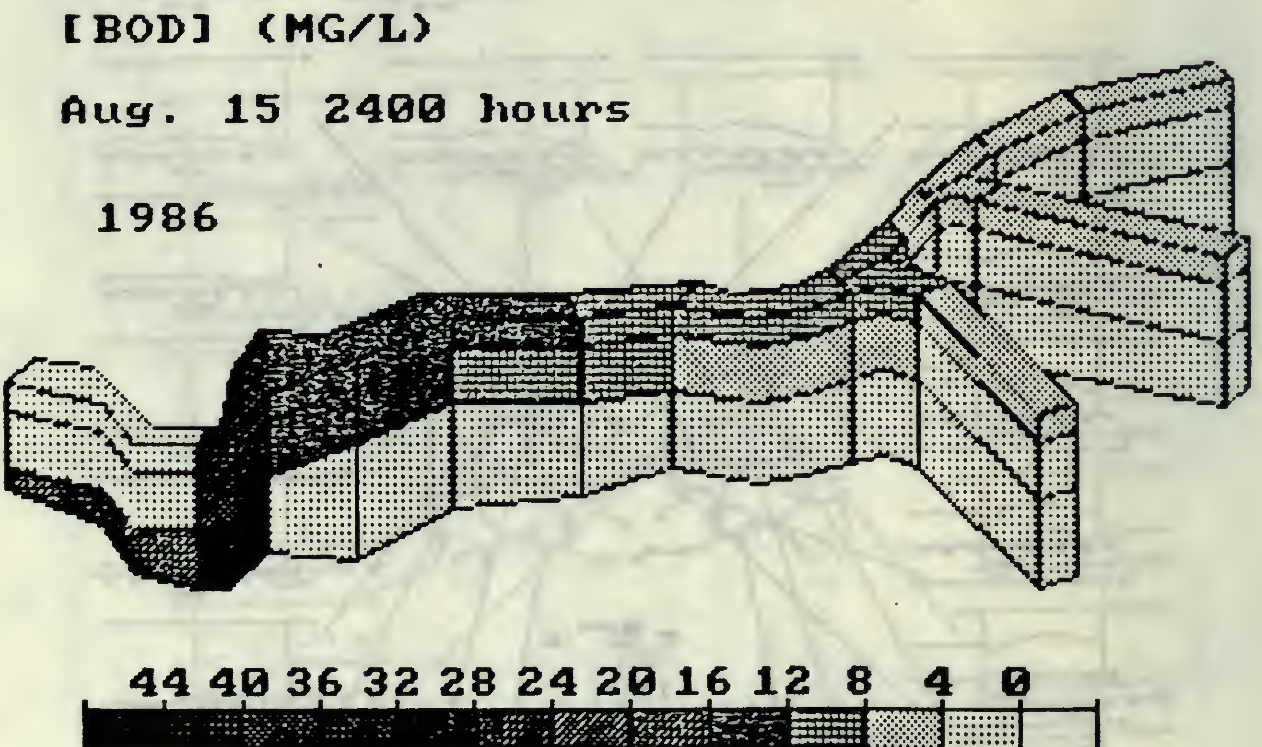


Figure 8. DO and BOD August 15, 1986 in 3-D

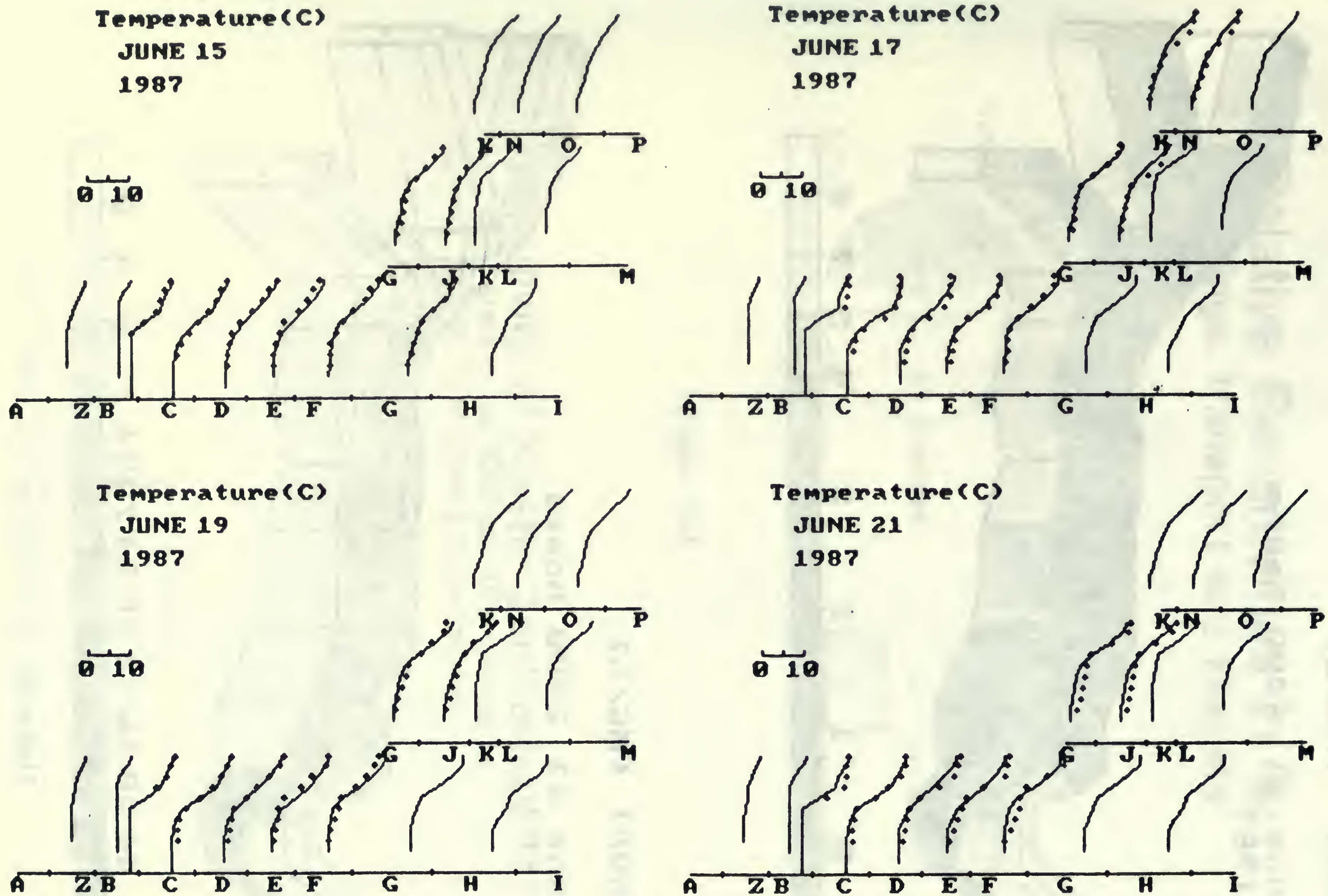
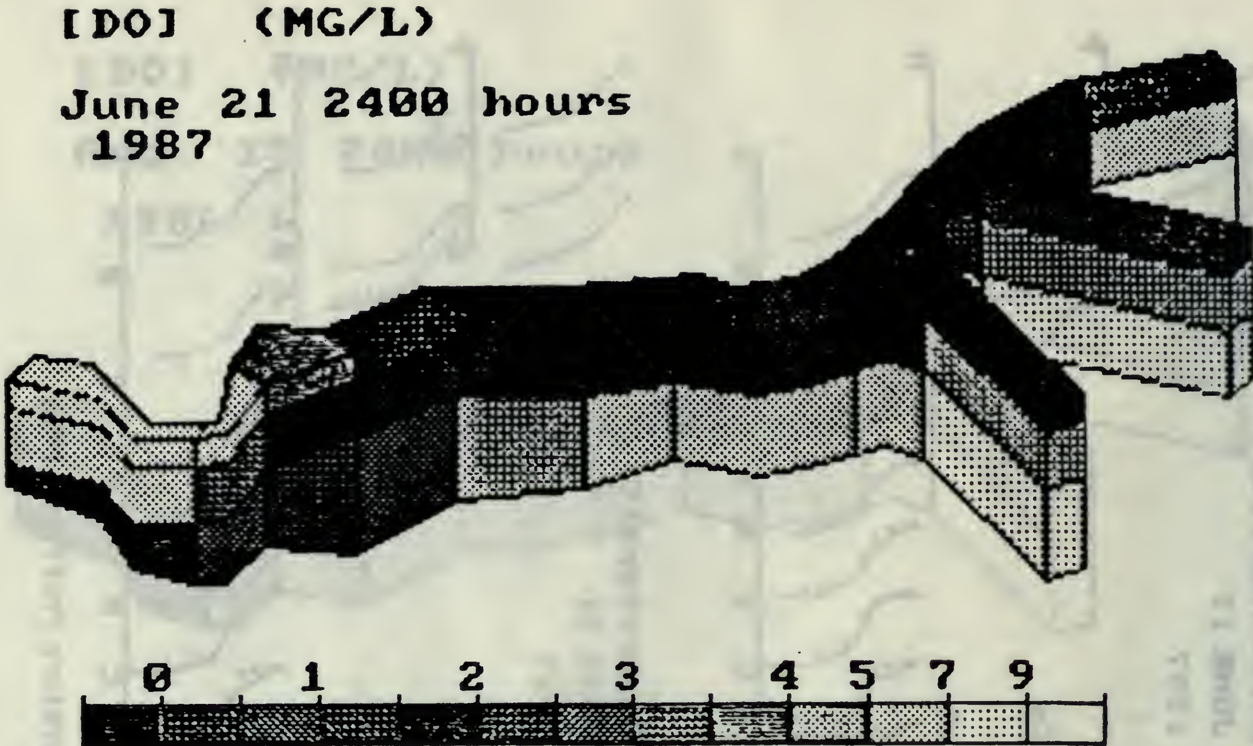


Figure 9. Simulated and Observed Temnerature Profiles, 1987



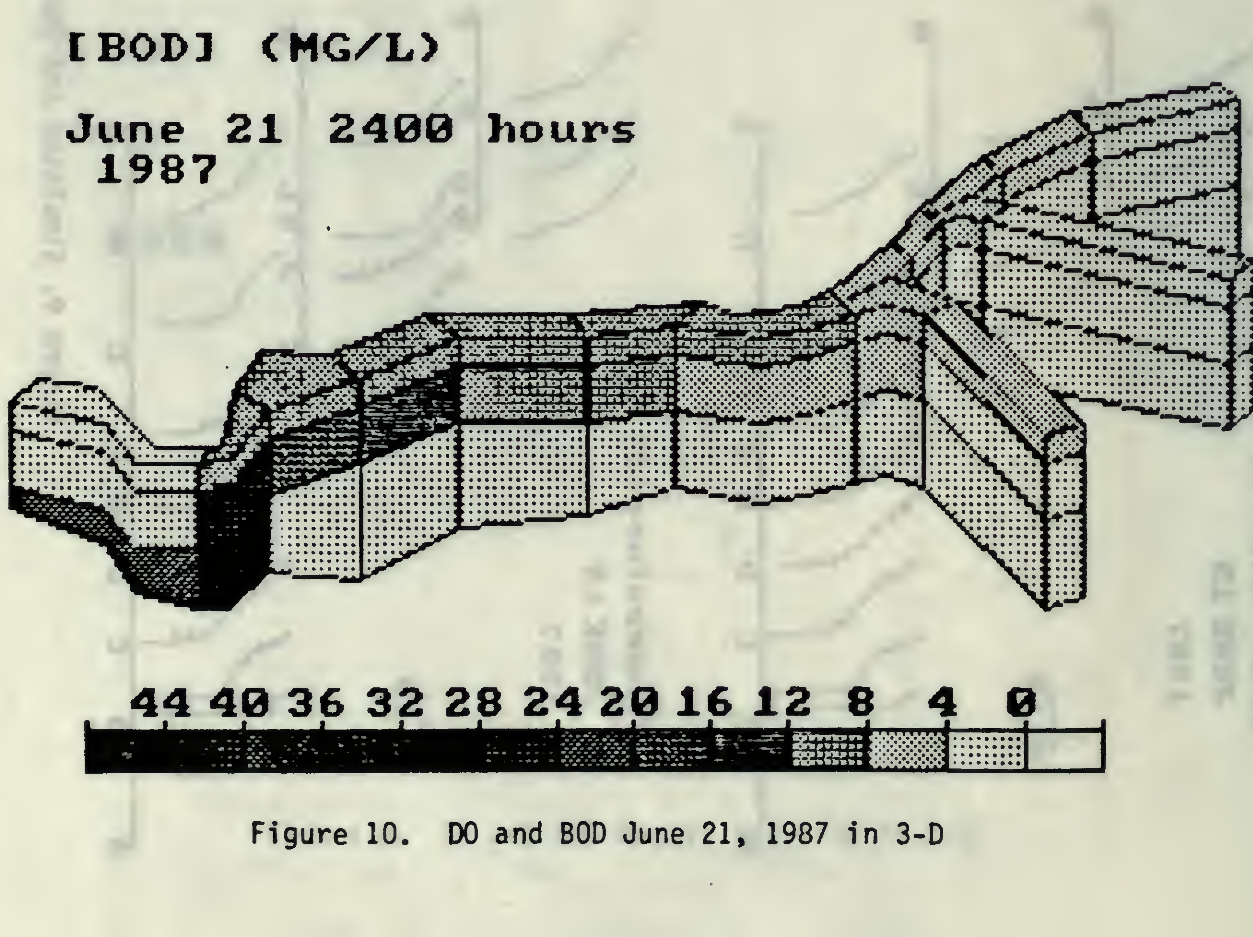


Figure 10. DO and BOD June 21, 1987 in 3-D

Relative Sensitivities in %:
Loadings, transport and kinetics

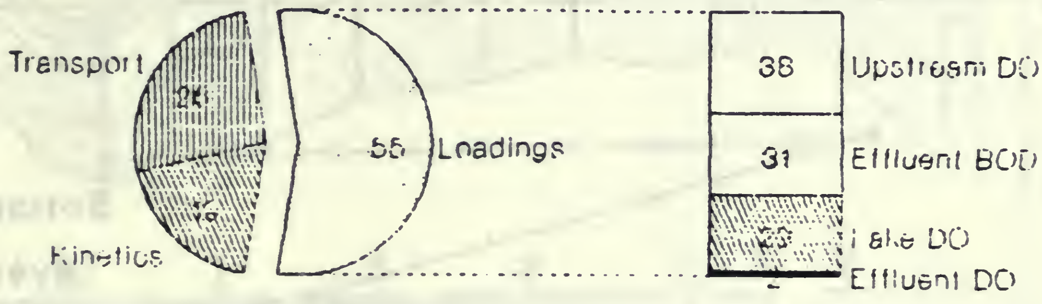


Figure 11(a).

Sensitivity of Kinetic Coefficients
(% change in top [DO] for 40% change in kinetic coefficients in the model)

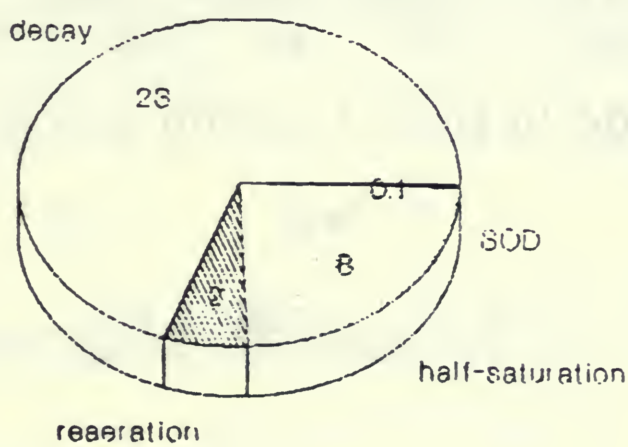


Figure 11(b).

Response of DO at GJ to BOD Loading Changes

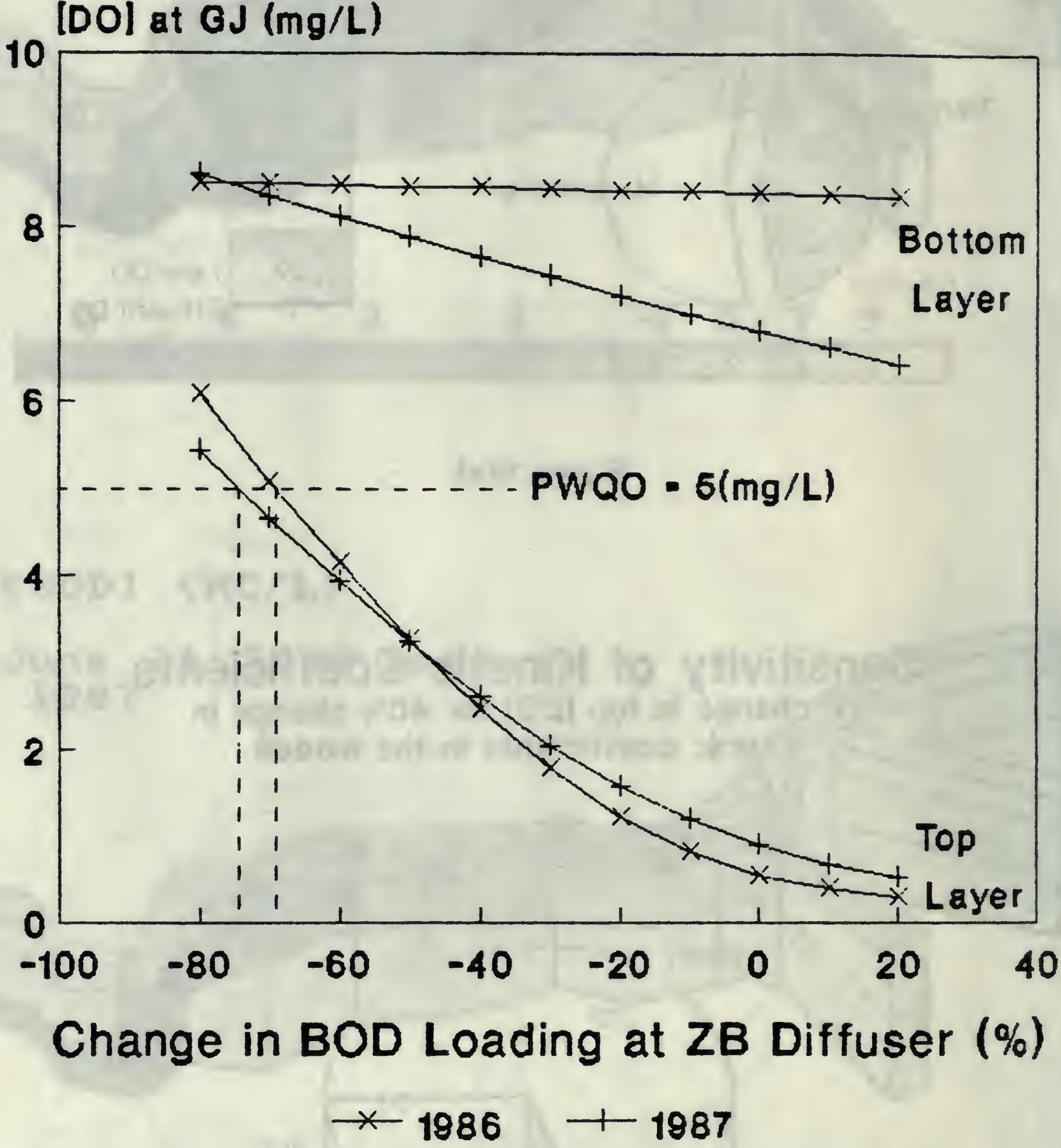


Figure 12

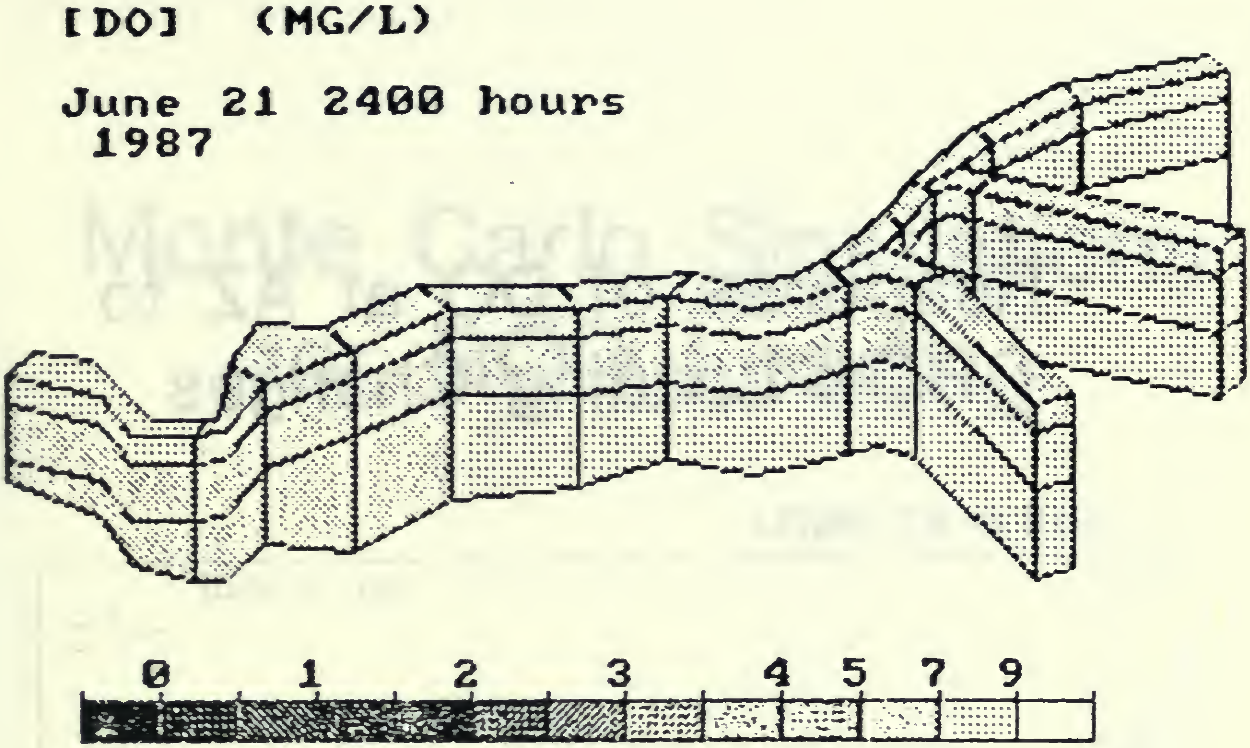


Figure 13. DO in 3-D June 21, 1987 with 80% BOD Load Reduction from ZB

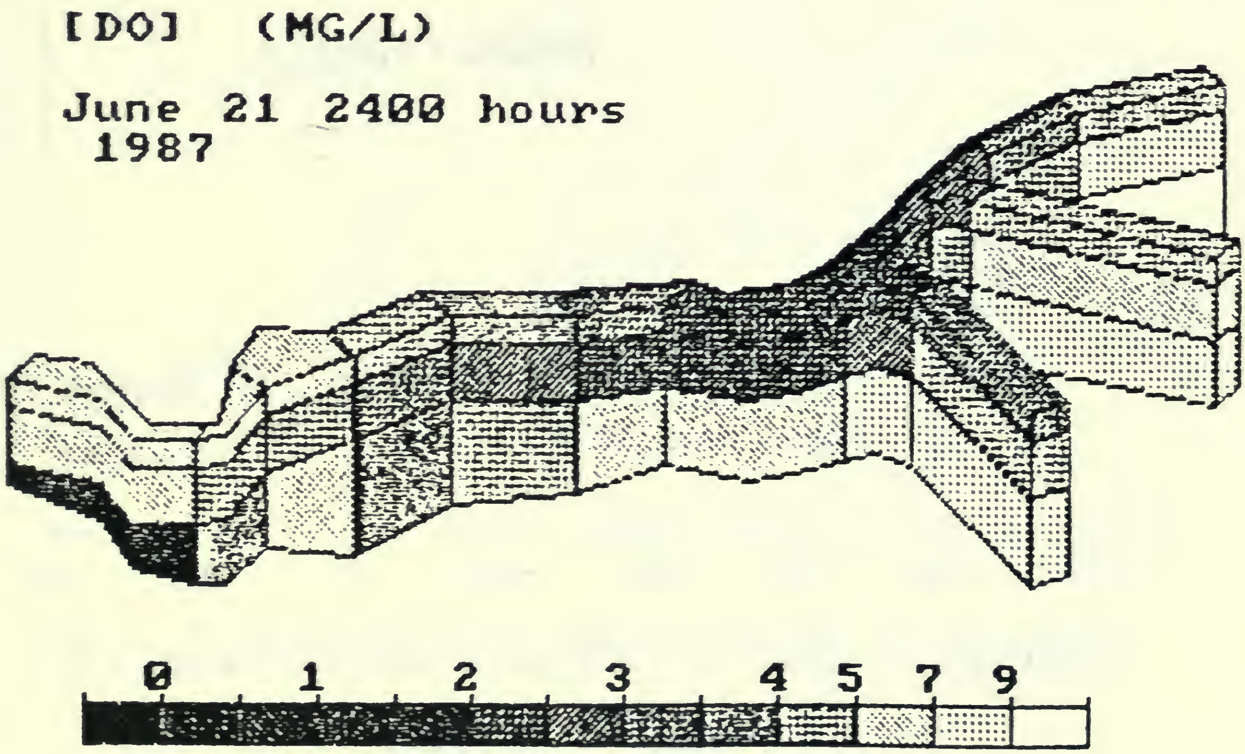


Figure 14. DO in 3-D June 21, 1987 with 10,000 kg/d DO Diffused into Segment BC

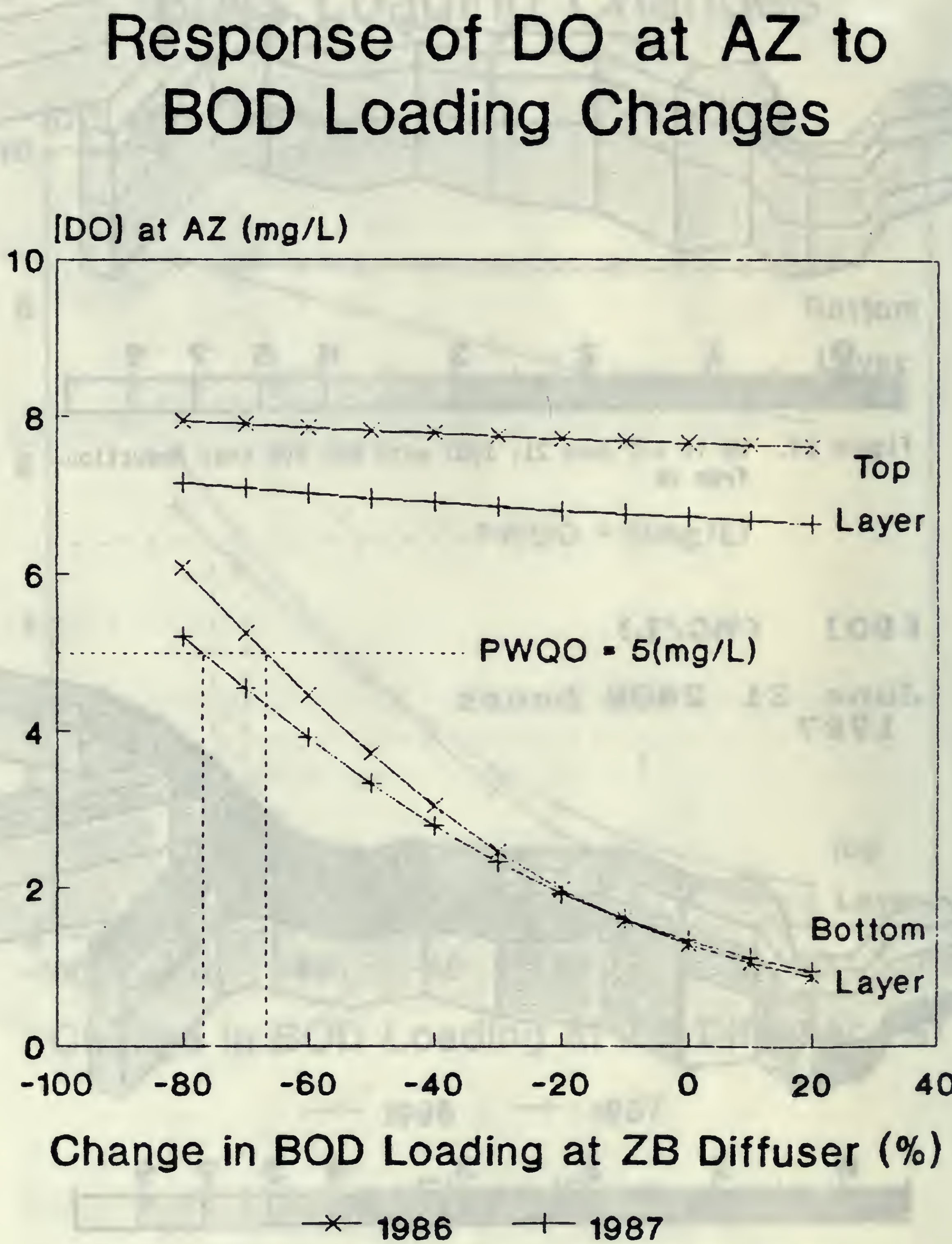

Response of DO at AZ to BOD Loading Changes
[DO] at AZ (mg/L)
10
8
6
4
2
0
Top Layer
PWQO = 5(mg/L)
Bottom Layer
-100
-80
-60
-40
-20
0
20
40
Change in BOD Loading at ZB Diffuser (%)
1986
1987

Figure 15

Monte Carlo Simulations for BOD Loading

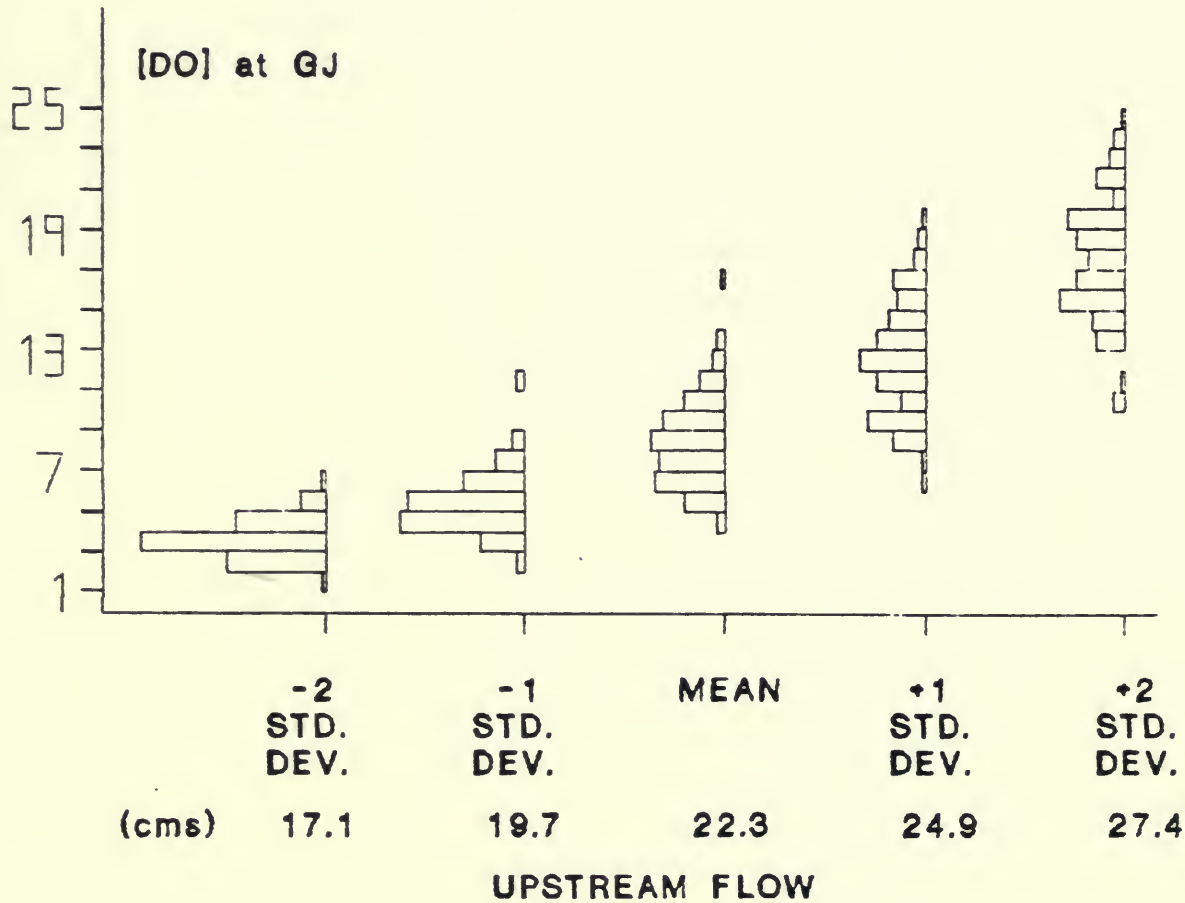
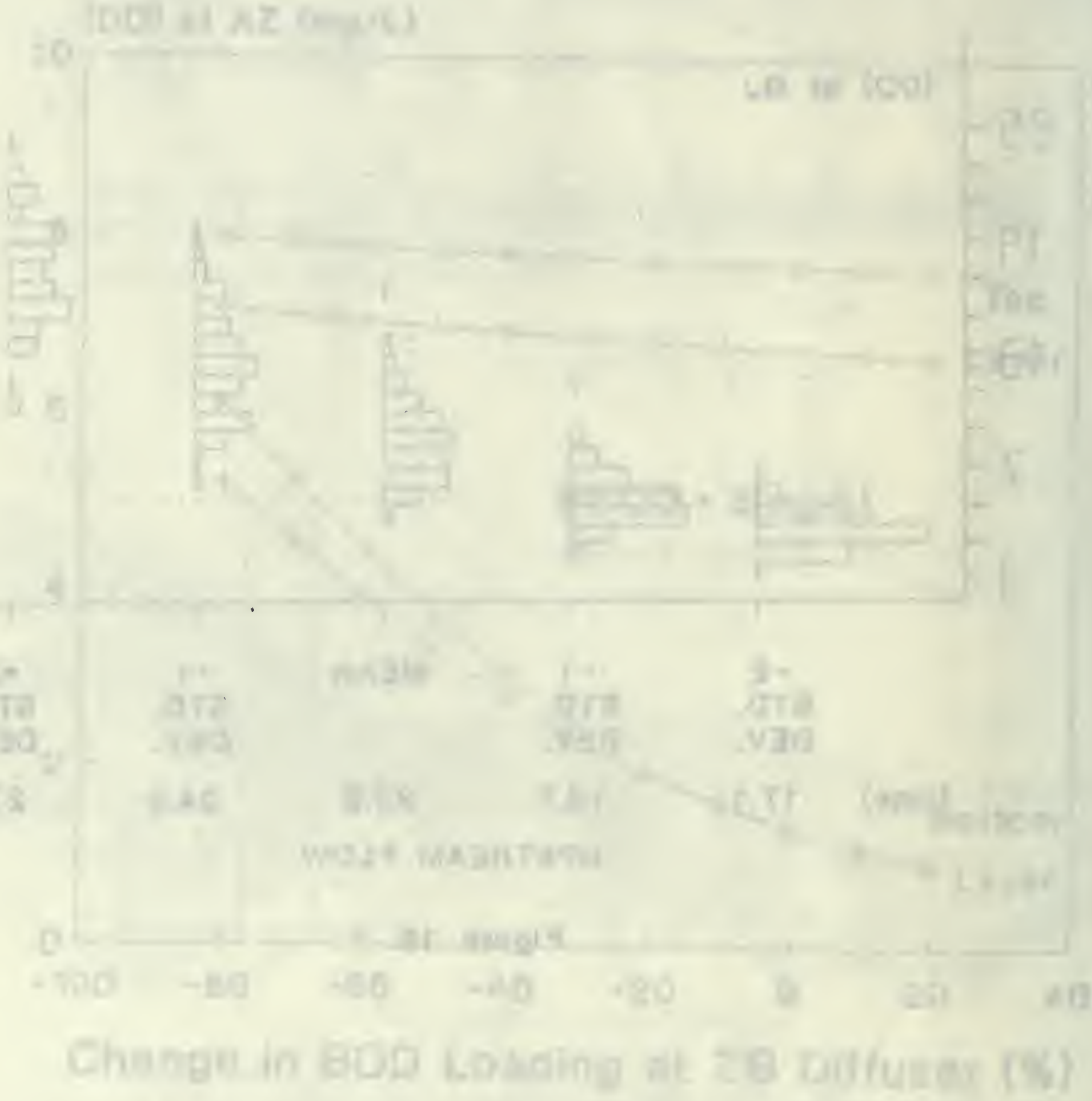


Figure 16.

Response of DO at AZ to BOD Loading Changes



Change in BOD Loading at ZB Diffuser (%)

Figure 15